A kilowatt-scale free electron laser driven by L-band superconducting linear accelerator operating in a burst mode

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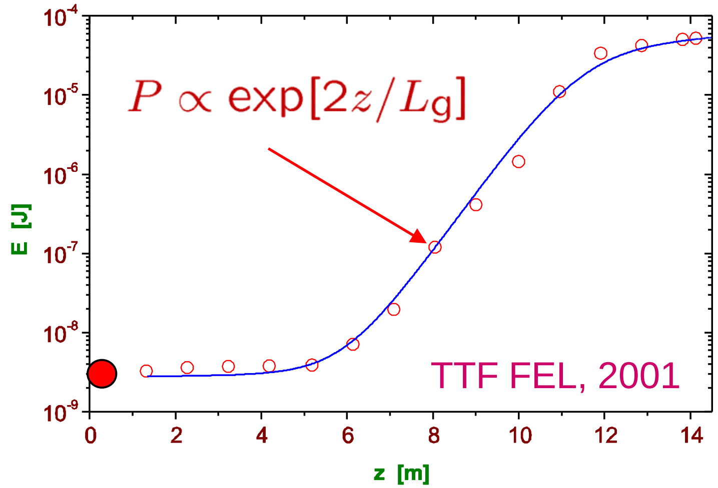
(DESY, Hamburg)

Outline:

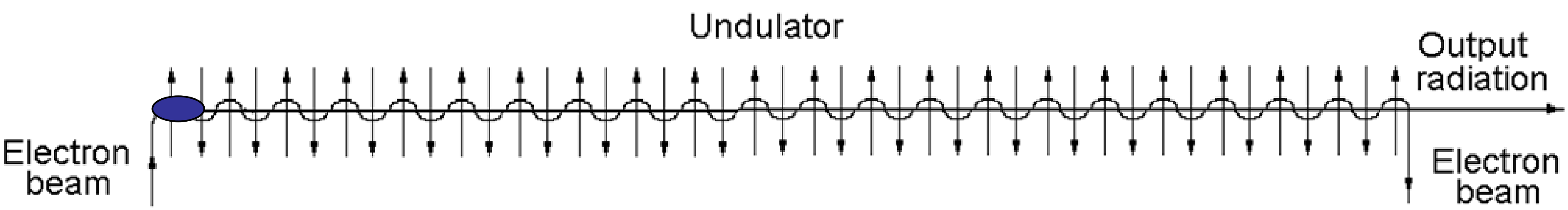
- Generation of high average radiation power with FLASH-like FEL.
- Current status of FLASH technology.
- Worldwide trends in FEL developments.
- Outlook in the future.

FLASH facility at DESY, Hamburg

Self Amplified Spontaneous Emission (SASE) FEL

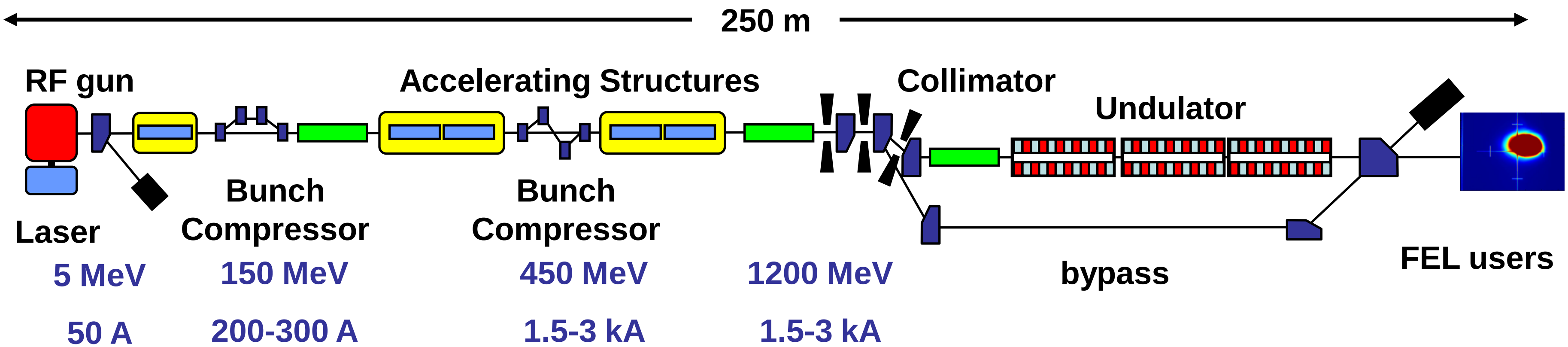


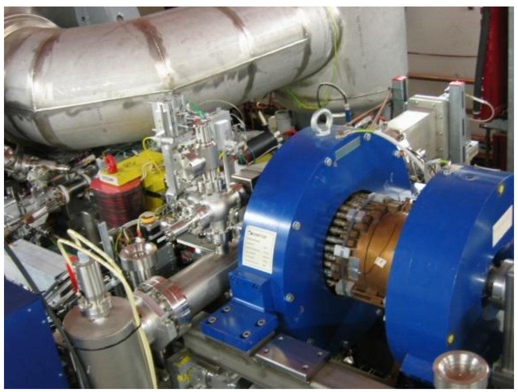
$$\lambda \simeq \lambda_w \frac{1+K^2}{2\gamma^2}.$$



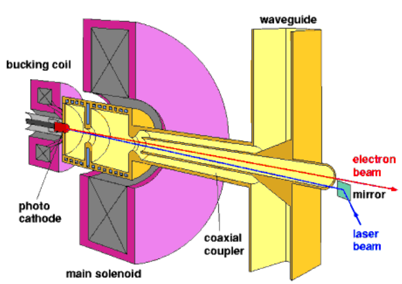
- Self Amplified Spontaneous Emission (SASE) FEL is an attractively simple device: it is just a system consisting of a relativistic electron beam and an undulator only.
- The FEL collective instability in the electron beam produces an exponential growth (along the undulator) of the modulation of the electron density on the scale of undulator radiation wavelength.
- SASE FEL is capable to produce high power and high quality radiation (in terms of coherence properties).

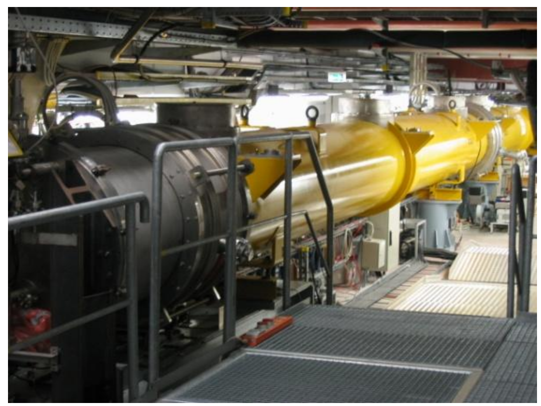
Free Electron Laser in Hamburg (FLASH)





Laser-driven rf gun





Superconducting accelerator

1.3 GHz, Nb, operates at 2 K,

Gradient up to 35 MV/m

Undulator

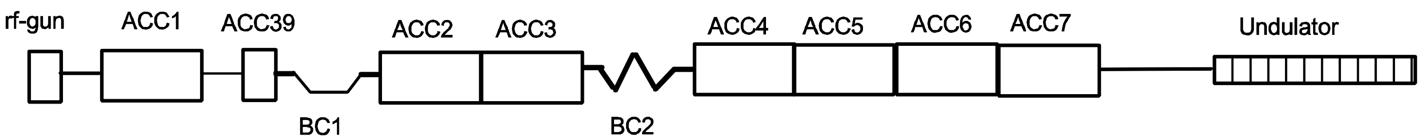
Hybrid, NdFeB

Period 2.73 cm

Peak field 0.48 T

Length 27 m

FEL source for NGL (FLASH technology)

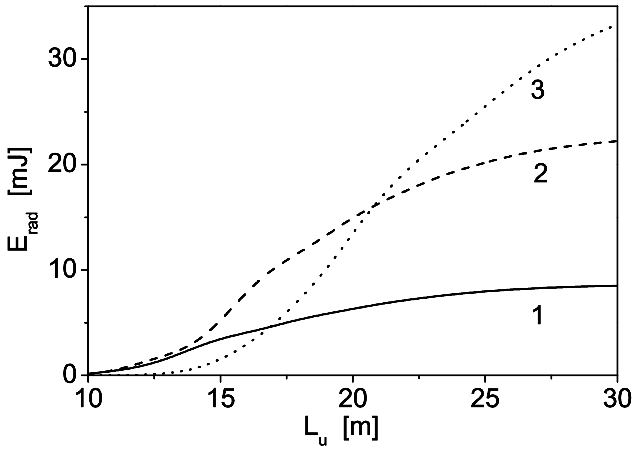


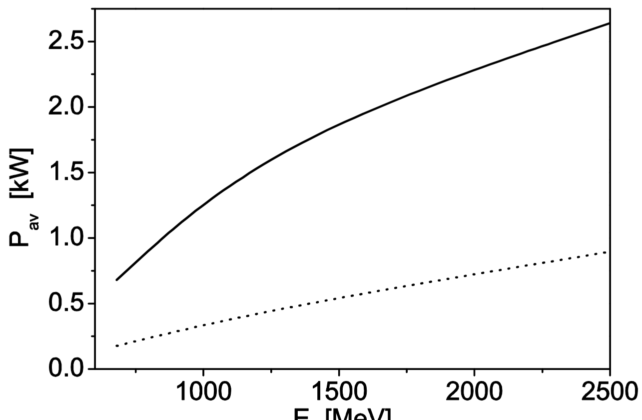
Present concept of the radiation source is based on FLASH technology:

- Production, acceleration, and compression of electron beams with small emittance (down to 1 mm-mrad at 1 nC).
- Use of full capabilities of superconducting accelerator in terms of average power (10 mA beam load within 0.8 ms macropulse duration at 10 Hz repetition rate = 100 kW at electron energy of 1.25 GeV).
- Use of single-pass FEL amplifier starting from shot noise in the electron beam (SASE FEL). Application of undulator tapering to increase FEL efficiency up to 2 – 2.5%.
- Generation of a kW-level average radiation power is possible at any wavelength of interest for lithography without change of hardware: just by tuning the undulator gap. Here we present examples for FEL source operating at 13.5 nm and 6.8 nm wavelengths.
- High quality radiation with diffraction limited divergence. Spectrum width of the radiation is about 1% which fits well the requirements.

13.5 nm FEL source for NGL (FLASH technology)

	FLASH	NGL-680	NGL-1250	NGL-2500
Electron energy, MeV	680	680	1250	2500
Bunch charge, nC	1	1	1	1
Peak current, A	2500	2500	2500	2500
Normalized emittance, mm-mrad	1.5	1.5	1.5	1.5
rms energy spread, MeV	0.5	0.5	0.5	0.5
Macropulse duration, ms	0.8	0.8	0.8	0.8
Micropulse rep. rate, MHz	9	10	10	10
# pulses in macropulse	7200	8000	8000	8000
Macropulse rep. rate, Hz	10	10	10	10
Undulator period, cm	2.73	2.73	3.7	5.0
Undulator length, m	27	30	30	30
Energy in the radiation pulse, mJ	1.4	8.5	22	33
Peak power, GW	5.6	34	88	130
Average radiation power, W	100	680	1760	2640





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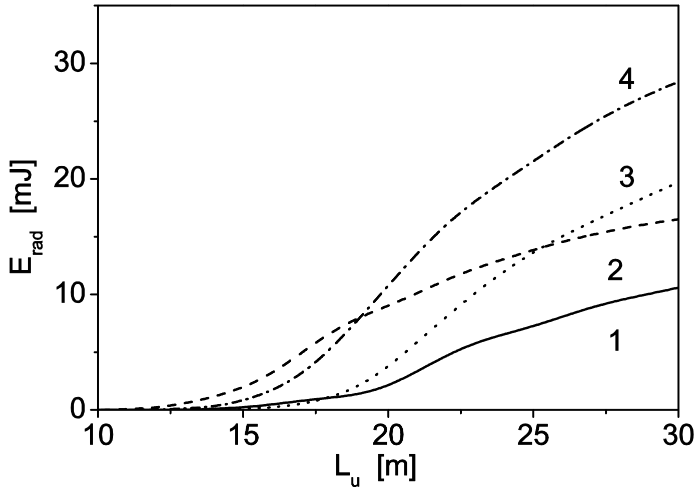
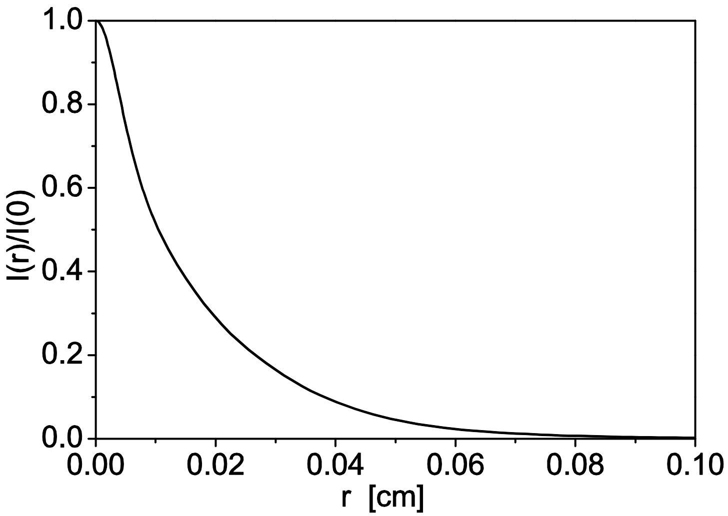
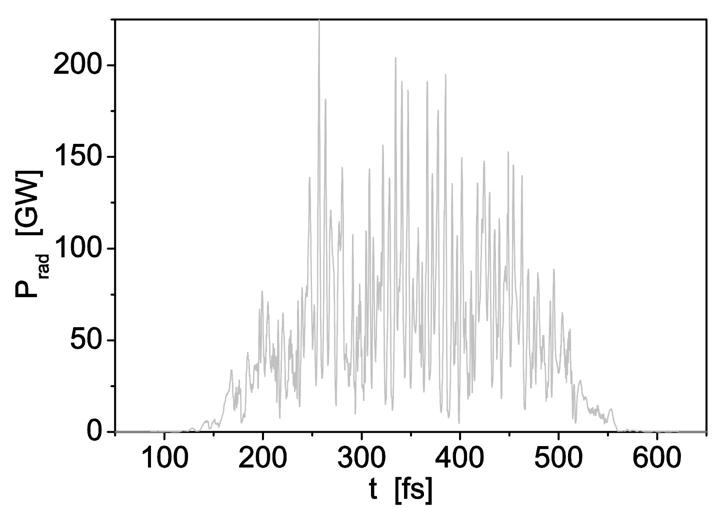
6.8 nm FEL source for NGL (FLASH technology)

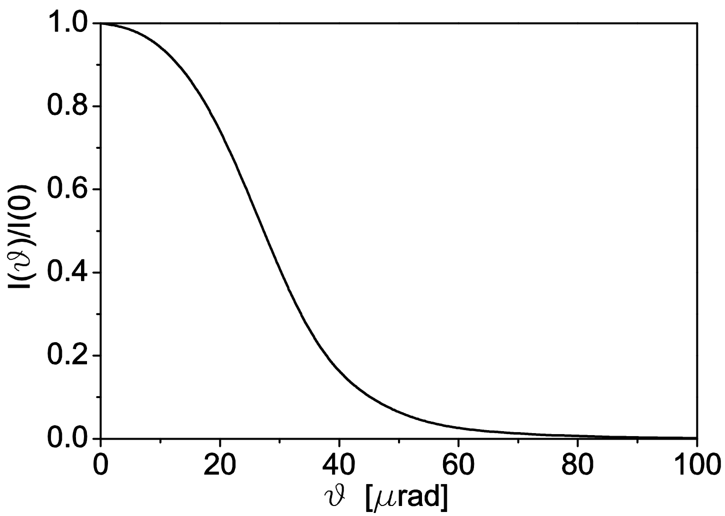
Electron energy, MeV	1250	1250	2500	2500
Bunch charge, nC	1	1	1	1
Peak current, A	2500	2500	2500	2500
Normalized emittance, mm-mrad	1.5	1	1.5	1
rms energy spread, MeV	0.5	0.5	0.5	0.5
Macropulse duration, ms	0.8	0.8	0.8	0.8
Micropulse rep. rate, MHz	10	10	10	10
# pulses in macropulse	8000	8000	8000	8000
Macropulse rep. rate, Hz	10	10	10	10
Undulator period, cm	3.7	3.7	5.0	5.0
Undulator length, m	30	30	30	30
Energy in the radiation pulse, mJ	11	16	20	28
Peak power, GW	44	64	80	110
Average radiation power, W	880	1280	1600	2240

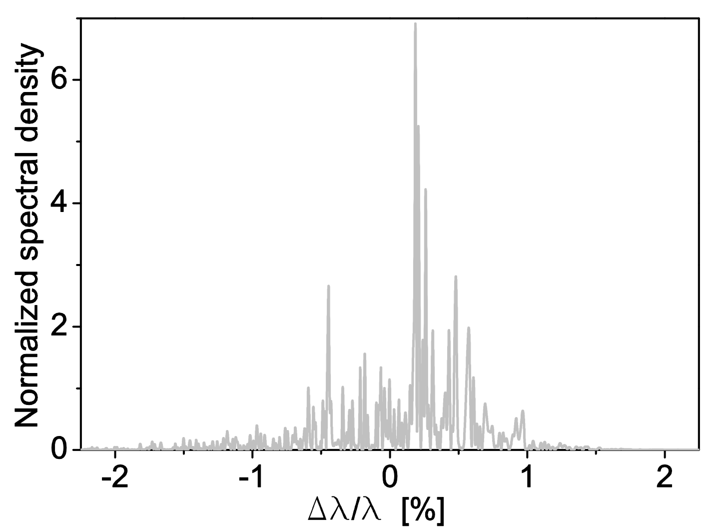


Characteristics of the radiation (13.5 nm, 1.25 GeV, P=1.7 kW)







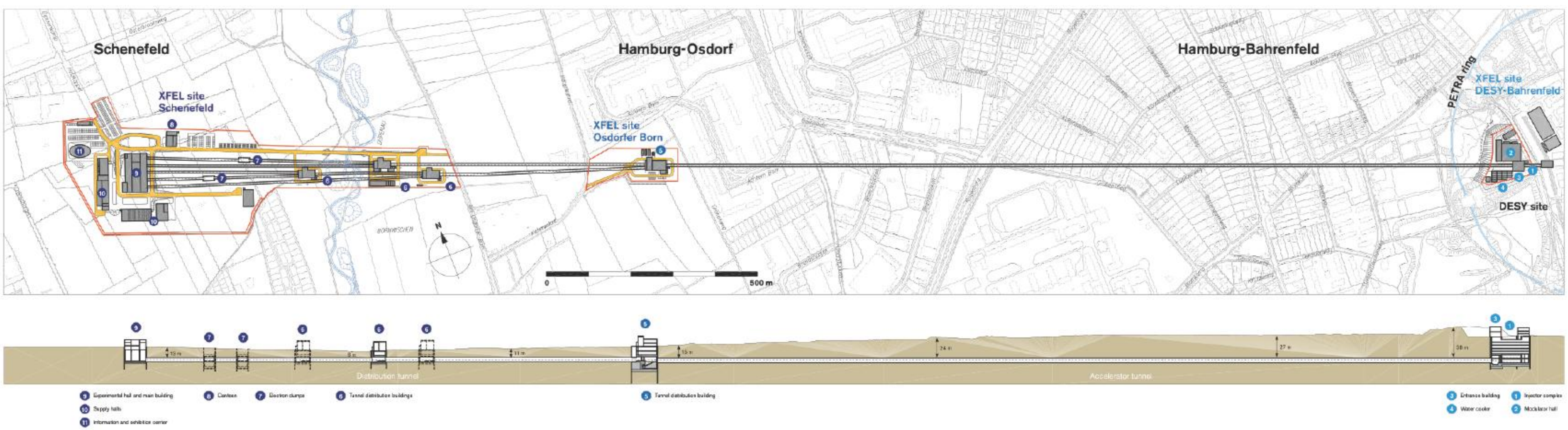


Diffraction limted photon beam

Temporal/spectral structure

European XFEL and industrialization of FLASH technology

- The internationally organized European X-ray free electron laser (XFEL) is under construction in Hamburg. The project is the first large scale application of the TESLA/FLASH technology developed over the last 15 years. Construction work along the 3.4 km European XFEL facility started early 2009. Start of the accelerator commissioning is scheduled for 2015.
- Electron beam energy is up to 17.5 GeV. The accelerator consists of 100 accelerating modules (800 superconducting accelerating structures, operating at a gradient of 24.3 MV/m. 25 RF stations will supply the necessary RF power.
- Three undulator beamlines with total magnetic length of undulators about 450 meters. Wavelength range is from 0.05 nm to 60 nm.
- The high level of industrialization of the main components for the European XFEL involving Thales, Toshiba, CPI, Research Instruments, E. Zanon, etc.



Worldwide trends in the FEL developments

Several dedicated FEL user facilities are in operation: LCLS, SACLA, FLASH, FERMI, SPARC, etc. Wavelength range spans from VUV to hard x-rays. Main trends of the developments are:

Obtaining shortest radiation wavelengths with SASE FEL:

- FLASH: 4.x nm – 47 nm.
- LCLS: 0.12 nm - 1.5nm.
- SACLA: 0.08 nm – 0.16 nm.

External seeding with frequency conversion:

- Harmonic generation in gas jet (HHG)+ FEL amplifier: SPRING-8, sFLASH.
- Frequency multiplication in the FEL amplifier (HGHG - high gain harmonic generation): FERMI in Trieste, SPARC in Frascati, NSLS at BNL.

Only FLASH technology is capable to produce high average power, but very limited opportunities for these developments are available at the user facility.

FLASH performance: 2006 versus 2011

	2006	2011
•Wavelength range:	13-47 nm	4.15-47 nm
•Pulse energy average:	up to 100 uJ	up to 300 uJ
•Average power:	up to 0.1 W	up to 0.3 W
•Pulse duration (FWHM):	10-50 fs	20-200 fs

- FLASH followed mainstream of the user facility development. Several upgrades aimed in the increase of the beam energy (up to 1.2x GeV) and user capabilities in terms of wavelength extension and organization of pump-probe experiments with external seeding (sFLASH).
- A progress in terms of average FEL power during last five years is rather moderate. Meanwhile, potential for high electron beam power (9 mA average current) has been demonstrated.
- Single-pulse FEL intensities are in agreement with expectations with an accuracy of a factor of two. Relevant studies are on track.
- No stop over is seen on the way to obtain high average FEL power. However, its demonstration needs dedicated slot in the FLASH schedule. Topic is still under discussion.

Summary (1)

- Physical principles of operation of the proposed FEL source (SASE FEL) have been demonstrated experimentally in many laboratories (DESY, SLAC, SPRING8, etc).

- Powerful FEL source can be constructed now without additional R&D using components of FLASH and European XFEL produced by industry. An example of a high degree of industrialization is the European XFEL.

- However, full-power operation of FLASH FEL was not demonstrated yet. One of the reasons for this is tight program of the FLASH user facility. - allocation of beam time at FLASH is a subject of strong competition.

- **An official establishment of technological collaboration between DESY and industry will help to allocate time needed for high power FEL developments at FLASH.** An example is collaboration of institutes working in the framework of International Linear Collider (ILC) which pushes forward high average beam current developments.

Summary (2)

- Within a concept of a burst mode of operation there is a room for further optimization of the FEL source like increase of the average power (at a reduced macropulse repetition rate), or increase of the macropulse repetition rate for the price the output power reduction. This kind of considerations has been already analyzed in the framework of the European XFEL project.

- TESLA Technical Collaboration also develops extensions towards increase of the duty factor up to cw mode of operation and implementation of energy recovery. Note that our first proposal of the FEL source for the NGL (C. Pagani et al., NIMA 463(2001)9) has been based on these principles.

- The necessary replacement of klystrons by Inductive Output Tubes (IOT) seems to be possible. Serious problem is that of a high duty cycle or cw injector generating low emittance beams. When the injector technology becomes available, the FEL based radiation source can operate in cw mode. Application of energy recovery will allow to go over to higher output radiation powers (multi ten kW).

- **Construction of a dedicated FEL facility can be an essential subject for collaboration between R&D departments of microelectronic industry and developers of accelerator and FEL techniques** (see next talk by Evgeny Syresin from the Joint Institute for Nuclear Research, Dubna).

From single source- single tool approach to single source – multiple tools

Specific features of FLASH-type FEL (pulse train diagram and simplicity of transportation of optical beam) allow break the standard approach and easily organize simultaneous operation of multiple tools driven by a single SASE FEL. A photon beam distribution system based on movable multilayer mirrors can provide an efficient way to generate a multi-tool factory. Distribution of photons is achieved on the basis of pulse trains and it is possible to partition the photon beam among a few tens of independent tools working in parallel. A similar approach has been considered for the European X-ray FEL (TESLA-FEL 2004-02, DESY, Hamburg, 2004):